Simulation and inversion of borehole temperature profiles in surrogate climates: Spatial distribution and surface coupling

J. F. González-Rouco,[1] H. Beltrami,[2] E. Zorita,[3] and H. von Storch[3]

Received 22 September 2005; revised 21 November 2005; accepted 1 December 2005; published 10 January 2006.

[1] A heat-conduction forward model driven by ground surface temperature from three 1000-year climate simulations with the *state-of-the-art* ECHO-g model has been used to simulate underground temperature perturbation profiles. An inversion approach has been applied to reconstruct ground surface temperature histories from the simulated profiles and to compare them with the climate model temperatures. Results support the skill of borehole inversion methods to retrieve long-term temperature trends, and the robustness of using the present-day borehole network for reconstructing SAT variations.
Citation: González-Rouco, J. F., H. Beltrami, E. Zorita, and H. von Storch (2006), Simulation and inversion of borehole temperature profiles in surrogate climates: Spatial distribution and surface coupling, *Geophys. Res. Lett.*, *33*, L01703, doi:10.1029/2005GL024693.

1. Introduction

[2] Knowledge of the evolution of the global and hemispheric surface air temperature (SAT) through the last millennium is important to place recent warming in a broader temporal perspective. Beyond the instrumental period, climatological evidence relies on the availability and quality of a variety of proxy records and on the skill of a few methodological approaches to interpret them as SAT variations [*Briffa and Osborn*, 2002].

[3] Borehole temperature profiles (BTP) have been one of such sources of information which have significantly contributed to our understanding of centennial temperature changes. Climate reconstruction based on BTPs hinges on the assumption that SAT changes are coupled to ground surface temperature (GST) changes and propagate to the subsurface by thermal conduction. This approach has offered a rather singular view of the amplitude of global and hemispheric warming along the last five centuries [*Huang et al.*, 2000; *Harris and Chapman*, 2001; *Beltrami*, 2002; *Pollack and Smerdon*, 2004], only supported by some proxy reconstructions preserving low frequency variability [*Esper et al.*, 2002; *Moberg et al.*, 2005]. The different magnitude of SAT changes inferred from borehole inversions and those based on other proxy reconstructions [*Briffa and Osborn*, 2002] has fostered recent controversy and examination of critical aspects in borehole reconstructions [*Pollack and Smerdon*, 2004, and references therein].

[4] One strategy to test methods and assumptions in reconstruction approaches has been to use simulations with General Circulation Models (GCM) as surrogates for the real climate evolution. Rather than representing the true past climate, the simulations are meant to be plausible realizations compatible with the imposed GCM external forcing, complex enough to test the realism of the target reconstruction technique [*Zorita et al.*, 2003; *Rutherford et al.*, 2003; *von Storch et al.*, 2004]. Within the geothermal context, *González-Rouco et al.* [2003] used a 1000 yr. long forced simulation of the ECHO-g model to show that SAT-GST variations were closely related at low frequencies, suggesting that snow cover, evaporation and other modeled surface processes should not prevent BTPs from keeping a record of long term SAT trends.

[5] This work presents a first attempt to produce numerical simulations of perturbation BTPs and replicate, within the simulated climate, the reconstruction methods based on them. A heat-conduction forward model is driven by surface temperature time series provided with the ECHO-g integrations in order to produce the perturbation profiles. An inversion model is subsequently used to recover GST histories and compare them with simulated SAT, thus mimicking the borehole approach to climate reconstruction. The procedure is further used to illustrate the effects of surface coupling and geographical distribution of real boreholes in the forward simulation and inversion of BTPs. Results support the skill of inversion methods to derive the long term trends simulated by the GCM and the adequacy of the present distribution of profiles for estimating terrestrial SAT variations.

2. Models and Simulations

[6] ECHO-g consists of the atmospheric and ocean GCMs ECHAM4 and HOPE-g [*Legutke and Voss*, 1999]. The horizontal resolution is T30 (ca. 3.75°) for the atmospheric component and T42 (ca. 2.8°) with grid refinement at low latitudes for the ocean. Vertical discretization incorporates 19 (20) levels for the atmosphere (ocean). A flux adjustment constant in time and zero spatial average is applied to avoid climate drift.

[7] SAT represents air temperature at 2 m. The soil model is a five layer finite-difference approximation of the diffusion equation on the T30 land-sea-mask grid shown in Figure 1a (grey shading). Ground temperature on the lowest level (9.83 m depth) is used in this analysis as GST. Vegetation is fixed to present day conditions. Vegetation

[1]Departamento de Astrofísica y CC. de la Atmósfera, Universidad Complutense de Madrid, Madrid, Spain.

[2]Environmental Sciences Research Centre, St. Francis Xavier University, Nova Scotia, Canada.

[3]Institute for Coastal Research, GKSS-Research Centre, Geesthacht, Germany.

0094-8276/06/2005GL024693

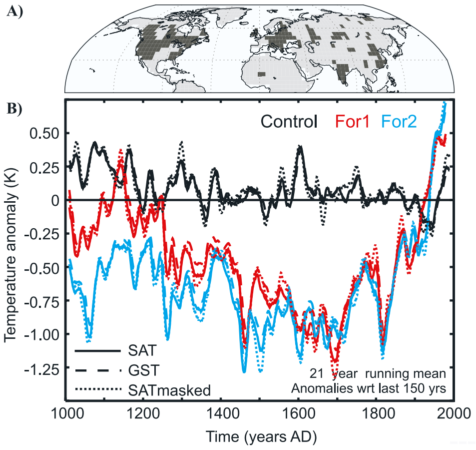

Figure 1. (A) Land sea mask of ECHO-g (light grey) and realistic distribution of NH borehole sites (dark grey) in the model. (B) Control and forced integrations (FOR1,2) NH SAT anomalies (dotted lines). SAT averages masked with the realistic borehole distribution shown in (A) and GST anomalies at 9.8 m depth (dashed lines) are shown for comparison.

effects on evapotranspiration, snow fall, snow accumulation, melting, infiltration and run-off are simulated [*Deutsches Klimarechenzentrum*, 1993]. ECHO-g has been extensively used and validated in numerous studies [e.g., *Raible et al.*, 2004].

[8] A 1000 year long control run with present external forcing and two forced simulations of the period 1000 to 1990 AD incorporating identical external forcing but different initial conditions were considered. Natural and anthropogenic estimates of the millennial evolution of external forcings (solar irradiance, radiative effects of stratospheric volcanic aerosols and greenhouse gas concentrations) were derived based on the reconstructions provided by *Crowley* [2000]. Further description of external forcing as well as results from these simulations are given by *von Storch et al.* [2004] and *Zorita et al* [2003, 2005].

[9] The forward model is used to derive grid-point perturbation BTPs 600 m deep using ECHO-g SAT and GST changes as boundary surface conditions. Yearly anomalies with respect to the long term mean are considered for this purpose. At each 1 m depth interval a temperature anomaly is evaluated from the surface thermal conditions using the solution of the heat conduction equation [*Beltrami and Bourlon*, 2004]. In order to illustrate the effect of uneven geographical sampling profiles are generated both for all NH terrestrial grid points (898) and for a realistic mask with 177 grid-points replicating the actual borehole network (dark shading in Figure 1a). An inversion model based on singular value decomposition (SVD [*Mareschal and Beltrami*, 1992]) is used to derive GST histories from grid-point BTPs. The thermal diffusivity used in the forward and inversion model was the same as in the ECHO-g GCM ($0.75\ 10^{-6}\ \mathrm{m^2\ s^{-1}}$). The model used for the inversion of each grid point profile consists of a series of 20-yr step changes in GST history with an eigenvalue cutoff set to 0.1 to produce stable solutions to all data noise conditions [*Mareschal and Beltrami*, 1992]. A NH reconstruction is obtained after latitude weighting and averaging of single inversions.

3. Results

[10] Figure 1b shows annual NH SAT anomalies in the control and forced (FOR1,2) simulations. In contrast to the rather stable behavior of the control integration, FOR1,2 show centennial variations in response to external forcing: an initial Medieval Warm period (MWP) gives way to a cold transition into a simulated Little Ice Age (LIA) which is disrupted by subsequent warming along the industrial era as described in previous works [*González-Rouco et al.*, 2003; *Zorita et al.*, 2005]. The amplitude of medieval warming is larger ($\sim 0.5K$) in FOR1 than in FOR2. FOR1 was started from a comparatively warmer state than FOR2 and both simulations were allowed a spin up period of one century to adapt to the forcing conditions of year 1000 AD. This illustrates the large impact of the initial conditions and, as suggested by other authors [*Goosse et al.*, 2005], the convenience of using longer, and costly, spin-up periods.

[11] These integrations reproduce a complex environment of hydrological and thermal surface climate interactions which makes them suitable for assessing models and assumptions in climate reconstruction approaches. Figure 1b illustrates two aspects of relevance for borehole climatology [*Pollack and Smerdon*, 2004]: SAT vs. GST coupling and the effect of uneven geographical sampling of borehole sites (Figure 1a). Low-pass filtered NH GST at 9.8 m depth and SAT sampled on realistic distribution of borehole sites are plotted for comparison with NH terrestrial SAT. The long term coupling between SAT and GST does not seem to be affected by snow cover changes, evaporation and other potential surface climatic processes, both in the control and the forced simulations. This extends the results of *González-Rouco et al.* [2003] for different realizations with and without external forcing. Thus, the SAT-GST coupling is not simulation dependent, nor does it depend on the low frequency behavior imposed by including external forcing. As for the masked SAT, it can be also appreciated that it tracks the long term variations in NH SAT.

[12] Figure 2 provides some insight into these relations for shorter timescales than those in Figure 1b. Coherence and phase spectra of SAT vs. GST are shown for all simulations (Figure 2a). Coherence can be interpreted as a measure of correlation between SAT and GST at different timescales. Thus, it should be valued 1 under pure heat conduction conditions and will be affected only by perturbations derived from snow, evaporation and other simulated surface processes. SAT-GST coherence is high at long timescales and decreases with frequency. In turn, phase shows negligible values at timescales over 20 years and increases with frequency. This phase shift can be easily explained assuming the temperature signal is conducted downward as a sum of harmonics of frequency f. Each harmonic will be phase shifted an angle ϵ [*Mareschal and Beltrami*, 1992]: $\epsilon = z\sqrt{\pi f/\kappa}$; where z is depth and κ is diffusivity. ϵ variations with frequency at 9.8 m depth are shown to present good agreement with spectral phase shift in Figure 2a. Thus, in spite of potential climatological SAT-

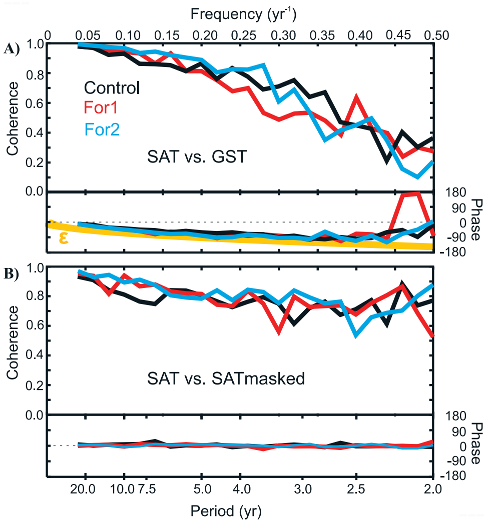

Figure 2. Coherence and phase spectra of NH SAT and GST (9.8 m) (A) and borehole masked SAT (B). The expected phase shift from conduction (ϵ) at different frequencies and 9.8 m depth is shown in (A) for comparison. 50 yr chunk length was used for the calculation involving the whole length of the simulations.

GST biases at the surface, the regime tends to be conductive at interannual to decadal timescales.

[13] Figure 2b shows cross spectra between NH SAT and the borehole-network sampled SAT. There is a general agreement, with stable phase and some increase of coherence with harmonic period. This can be attributed to lower frequencies being related to large scale, hemispheric or planetary disturbances, with less spatial degrees of freedom, which the borehole network has more potential to sample adequately.

[14] The behavior described above illustrates the frequency domain dependence of SAT-GST coupling and the minor relevance of irregular geographical sampling. The results are not dependent on the simulation, nor sensitive to changes in the external forcing. Thus, BTPs should retain a heat-conduction filtered version of SAT changes in spite of the decoupling effect of some surface disturbing factors and having an irregular geographical distribution [see references and discussion in *Pollack and Smerdon*, 2004]. The reliability of borehole reconstructions rests, among other unknowns, on this assumption and on the performance of inversion methods to retrieve GST histories from the BTPs. One way of assessing these uncertainties is simulating grid-point profiles driven by ECHO-g SAT and subsequently solving the inverse problem. Figure 3 offers this complementary view. Perturbation BTPs have been simulated using SAT time series from Control and FOR1,2 (Figure 3a, light shading). The SAT evolution represents the maximum thermal spread that can potentially propagate to the subsurface. Since this input could be perturbed by surface climate interactions (snow cover, evaporation, etc), a more realistic version of the downward propagating signal flowing into real profiles is estimated by considering temperature at the lowest soil model level (GST) and selecting only those grid points co-located with the realistic borehole sites (Figure 3a, dark shading). The resulting SAT-forced profiles illustrate the spread of surface temperature trends in the three ECHO-g simulations which qualitatively compares to that found in the observational data set [*Harris and Chapman*, 2001; *Beltrami*, 2002]. The borehole-network-masked profiles present a lower dispersion than the real data set due to a lower number of grid-points (177) than available in reality (ca. 900) and to the coarse resolution of the ECHO-g compared to the local character of real boreholes. The high frequency variations in SAT, or even in GST, have been filtered out by heat conduction. The control simulation presents some warming in the upper 50 meters as response to the warming during part of the last simulated century (Figure 1b) but only the forced simulations reflect a clear bias to warming in the upper 200 to 100 meters which is comparable to that in real boreholes and which corresponds to the warming simulated along the last 200 to 300 model years. Some cooling between 300 and ca. 150 m depth is apparent in the forced simulations registering the transition to the LIA in the simulated climate as shown bellow.

[15] A final step for the replication of the borehole-based climate reconstruction approach is shown in Figures 3b and 3c. Figure 3b displays the gridpoint inverted surface temperature histories, both for the SAT and for the GST driven

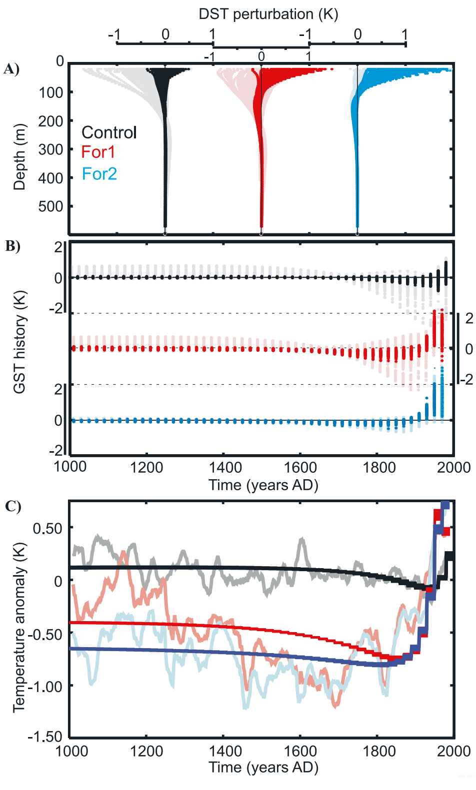

Figure 3. (A) Forward model simulation of BTPs with SAT series in NH grid-points (light shading) and driven with GST time series in the borehole selected grid points (Figure 1a). (B) Inverted GST histories derived from the profiles in (A). (C) 21 yr low pass filter of SAT and NH latitude weighted averages of profiles in (B). The differences between full NH-SAT profiles and borehole-GST profiles are shaded to highlight the spread and are bound (not shown) within the standard error of the estimated parameters for each solution [*Beltrami and Mareschal*, 1995].

profiles. Figure 3c compares the low frequency evolution of NH SAT (Figure 1b) with the latitude-weighted average of the inverted surface temperature histories in Figure 3b. The results using the SAT- and the selected GST-driven profiles are virtually identical and overlap in Figure 3c (minor differences fall within stability bands of the solution in each simulation). Furthermore, the borehole approach is able to retrieve the trend differences in control and forced simulation in the last few centuries of the simulations. Most part of the high frequency variability present in the NH SAT series is lost through soil conduction when applying the forward model and estimating back the surface temperature histories. It is remarkable that the SVD inversion is sensitive enough to reproduce a multi-century cooling trend, in FOR1-2, from the MWP to the simulated LIA and even to discern between the different degrees of simulated medieval warming.

4. Conclusions

[16] The control and forced climate simulations analyzed support the low frequency centennial tracking of SAT and GST changes with a more intense coupling at long timescales, and weakening with higher frequencies as expected from the influence of possible decoupling surface climate processes (evaporation, snow cover changes, etc.). The irregular and, in places sparse, distribution of borehole sites appears to be a sufficient sampling of NH terrestrial SAT.

[17] The simulation of temperature profiles and their posterior inversion supports the overall borehole methodology, showing that the retrieved GST histories forced with the SAT signal and the GST borehole-sites-masked signal are barely distinguishable. The forward simulated BTPs provide a reasonable comparison with the observational data set, revealing that only the forced simulations deliver a comparable warming in the top 100 to 200 meters.

[18] SVD inversion is able to retain the main features of the lowest frequency trends through the simulated millennium. Filtered through heat conduction, the last centuries of warming dominate and are well preserved in the borehole inversions. Furthermore, the method is also sensitive to the remote simulated past, discerning the different level of warming in the early centuries in the control and forced simulations. For the MWP and transition to LIA the method offers a quasi linear trend estimate of past temperatures in which warm and cold periods are averaged out [*Beltrami and Mareschal*, 1995]. Though tests with synthetic data have been performed with inversion methods [*Shen et al.*, 1992], this constitutes a first attempt to explore their performance in the large scale realistic environment in which multi centennial climate variability is simulated by a 'state-of-the-art' climate model.

[19] This suggests that if the quality of available BTPs improves and pending uncertainties are dealt with, the method itself has the potential to determine from the subsurface thermal evidence whether a MWP existed. Interestingly, neither in the analyzed grid-point inversion profiles, nor in the weighted hemispheric averages, did we find any evidence of the method to overestimate past temperature changes.

[20] **Acknowledgments.** We thank two anonymous reviewers and B. Stevens for comments. This work was partially funded by the EUproject SO&P, projects REN2002-04584-C04-CLI and CGL2005-06097 of the spanish MEC and in Canada by NSERC, CFCAS and AIF.

References

Beltrami, H. (2002), Earth's long term memory, *Science*, *297*, 206–207.

Beltrami, H., and E. Bourlon (2004), Ground warming patterns inthe Northern Hemisphere during the last five centuries, *Earth Planet. Sci. Lett.*, *227*, 169–177.

Beltrami, H., and J. C. Mareschal (1995), Resolution of ground temperature histories inverted from borehole temperature data, *Global Planet. Change*, *11*, 57–70.

Briffa, K. R., and T. J. Osborn (2002), Blowing hot and cold, *Science*, *295*, 2227–2228.

Crowley, T. J. (2000), Causes of climate change over the past 1000 years, *Science*, *289*, 270–277.

Deutsches Klimarechenzentrum (1993), The ECHAM3 Atmospheric General Circulation Model, *DKRZ Tech. Rep.*, *6*, Hamburg, Germany.

Esper, J., E. R. Cook, and F. Schweingruber (2002), Low-frequency signals in long tree-ring chronologies for reconstructing past temperature variability, *Science*, *295*, 2250–2253.

Goosse, H., T. J. Crowley, E. Zorita, C. M. Ammann, H. Renssen, and E. Driesschaert (2005), Modelling the climate of the last millennium: What causes the differences between simulations?, *Geophys. Res. Lett.*, *32*, L06710, doi:10.1029/2005GL022368.

González-Rouco, J. F., H. von Storch, and E. Zorita (2003), Deep soil temperature as a proxy for surface air-temperature in a coupled model simulation of the last thousand years, *Geophys. Res. Lett.*, *30*(21), 2116, doi:10.1029/2003GL018264.

Harris, R. N., and D. S. Chapman (2001), Mid-latitude (30–60 N) climatic warming inferred by combining borehole temperatures with surface air temperatures, *Geophys. Res. Lett.*, *28*, 747–750.

Huang, S., H. N. Pollack, and P. Y. Shen (2000), Temperature trends over the past five centuries reconstructed from borehole temperatures, *Nature*, *403*, 756–758.

Legutke, S., and R. Voss (1999), The Hamburg atmosphere-ocean coupled circulation model ECHO-G, *DKRZ Tech. Rep.*, *18*, Hamburg, Germany.

Mareschal, J. C., and H. Beltrami (1992), Evidence for recent warmingfrom perturbed thermal gradients: Examples from eastern Canada, *Clim. Dyn.*, *6*, 135–143.

Moberg, A., D. M. Sonechkin, K. Holmgren, N. M. Datsenko, and W. Karln (2005), Highly variable Northern Hemisphere temperatures reconstructed from low- and high-resolution proxy data, *Nature*, *433*, 613–617.

Pollack, H. N., and J. E. Smerdon (2004), Borehole climate reconstructions: Spatial structure and hemispheric averages, *J. Geophys. Res.*, *109*, D11106, doi:10.1029/2003JD004163.

Raible, C., U. Luksch, and K. Fraedrich (2004), Precipitation and Northern Hemisphere regimes, *Atmos. Sci. Lett.*, *5*, 43–55.

Rutherford, S., M. E. Mann, T. L. Delworth, and R. J. Stouffer (2003), Climate field reconstruction under stationary and non stationary forcing, *J. Clim.*, *16*, 462–479.

Shen, P. Y., K. Wang, H. Beltrami, and J. C. Mareschal (1992), A comparative study of inverse methods for estimating climatic history from borehole temperature data, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *98*, 113–127.

von Storch, H., E. Zorita, Y. Dimitriev, F. Gonzalez-Rouco, and S. Tett (2004), Reconstructing past climate from noisy data, *Science*, *306*, 679–682.

Zorita, E., J. F. González-Rouco, and S. Legutke (2003), Statistical temperature reconstruction in a 1000-year-long control climate simulation an excercise with Mann's et al. (1998) method, *J. Clim.*, *16*, 1378–1390.

Zorita, E., J. F. González-Rouco, H. von Storch, J. P. Montávez, and F. Valero (2005), Natural and anthropogenic modes of surface temperature variations in the last thousand years, *Geophys. Res. Lett.*, *32*, L08707, doi:10.1029/2004GL021563.

H. Beltrami, Environmental Sciences Research Centre, St. Francis Xavier University, P.O. Box 5000, Antigonish, NS, Canada B2G 2W5. (hugo@stfx.ca)

J. F. González-Rouco, Facultad CC. Físicas, Universidad Complutense de Madrid, E-28040 Madrid, Spain. (fidelgr@fis.ucm.es)

H. von Storch and E. Zorita, GKSS-Research Centre, Max Planck Str. 1, D-21502 Geesthacht, Germany. (storch@gkss.de; zorita@gkss.de)